TILDA

Towards Industrial LES/DNS in Aeronautics
Paving the Way for Future Accurate CFD

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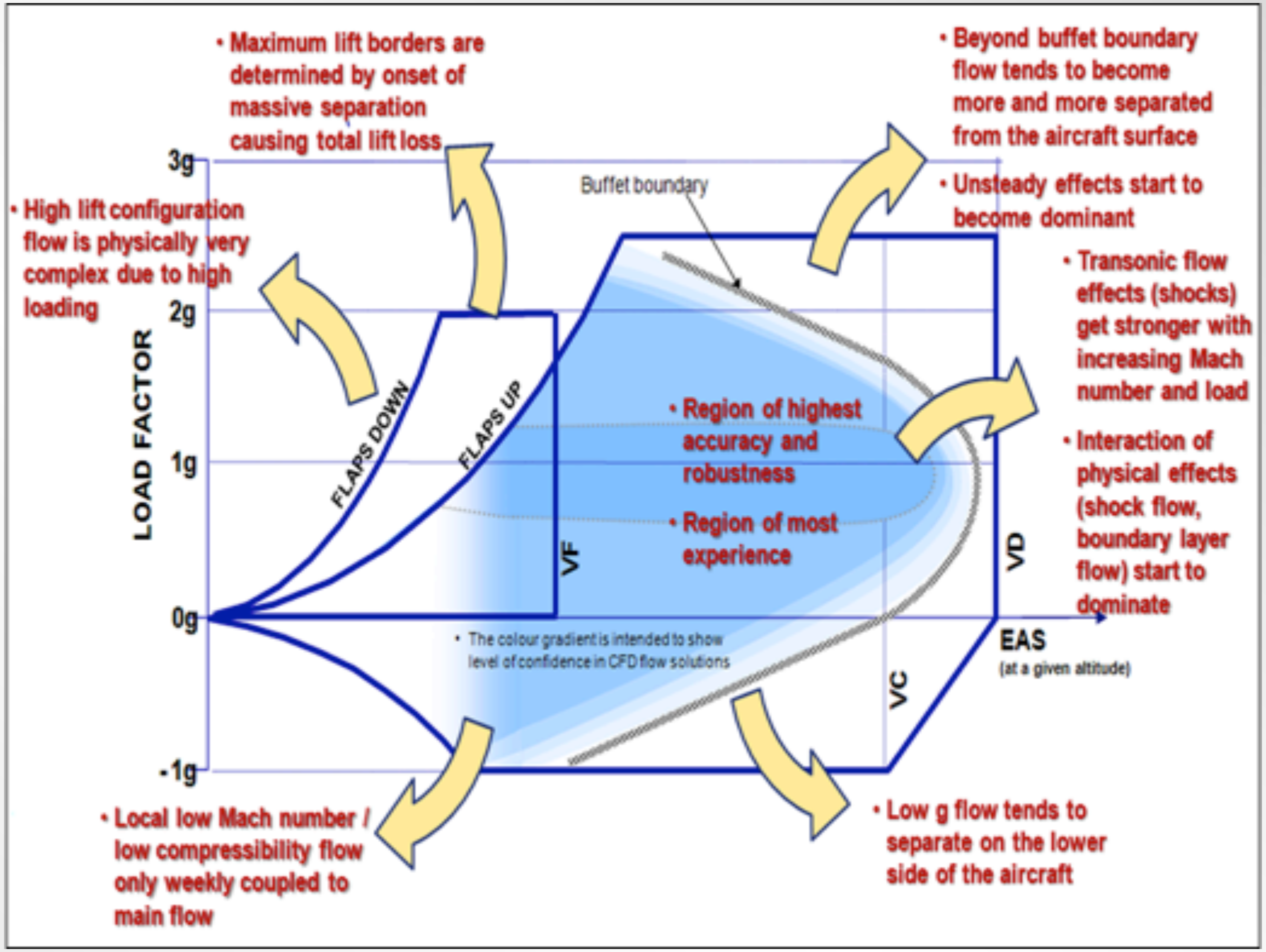
NUMECA INTERNATIONAL

Content

- Current CFD limitations
- The visions of future CFD
- The TILDA project
- Expected outcome for Industry

Current CFD capabilities and limitations

- CFD has progressed considerably in the last 50 years, due to algorithmic developments and growing capacities in computer hardware and HPC
- The current industrial practice relies essentially on RANS modeling, despite the strong limitations of present day turbulence (and transition) modelling
- The use of CFD has remained confined to a small region of the operating design space **due to the inability of current methods to reliably predict turbulent separated flows**



Flight envelopes and level of confidence in CFD solutions - given by colour gradient (Courtesy: Airbus, A. Abbas (2012))

Current Limitations of CFD in Aeronautics

How can we overcome these limitations

- There is a strong need to move beyond RANS based modeling and overcome the limitations of turbulence models, by moving towards LES/DNS levels of simulations

- Hybrid RANS-LES and wall-modeled LES offer a temporary intermediate option, although significant modeling issues remain to be addressed here as well

- **To achieve a higher level of predictive reliability, we need to reduce the level of empiricism**

- A growing number of LES/DNS simulations with fine mesh resolutions have been produced in recent years, mainly on basic simplified configurations

- **What is the road towards full LES/DNS capabilities at an industrial level in Aeronautics?**

The visions for next generation CFD

Two interesting overviews of the future of CFD have been provided recently by

- NASA vision CFD-2030 (2014)
- P. Spalart (2012) and P. Spalart and V. Venkatakrishnan (Aeronautical Journal 2016)

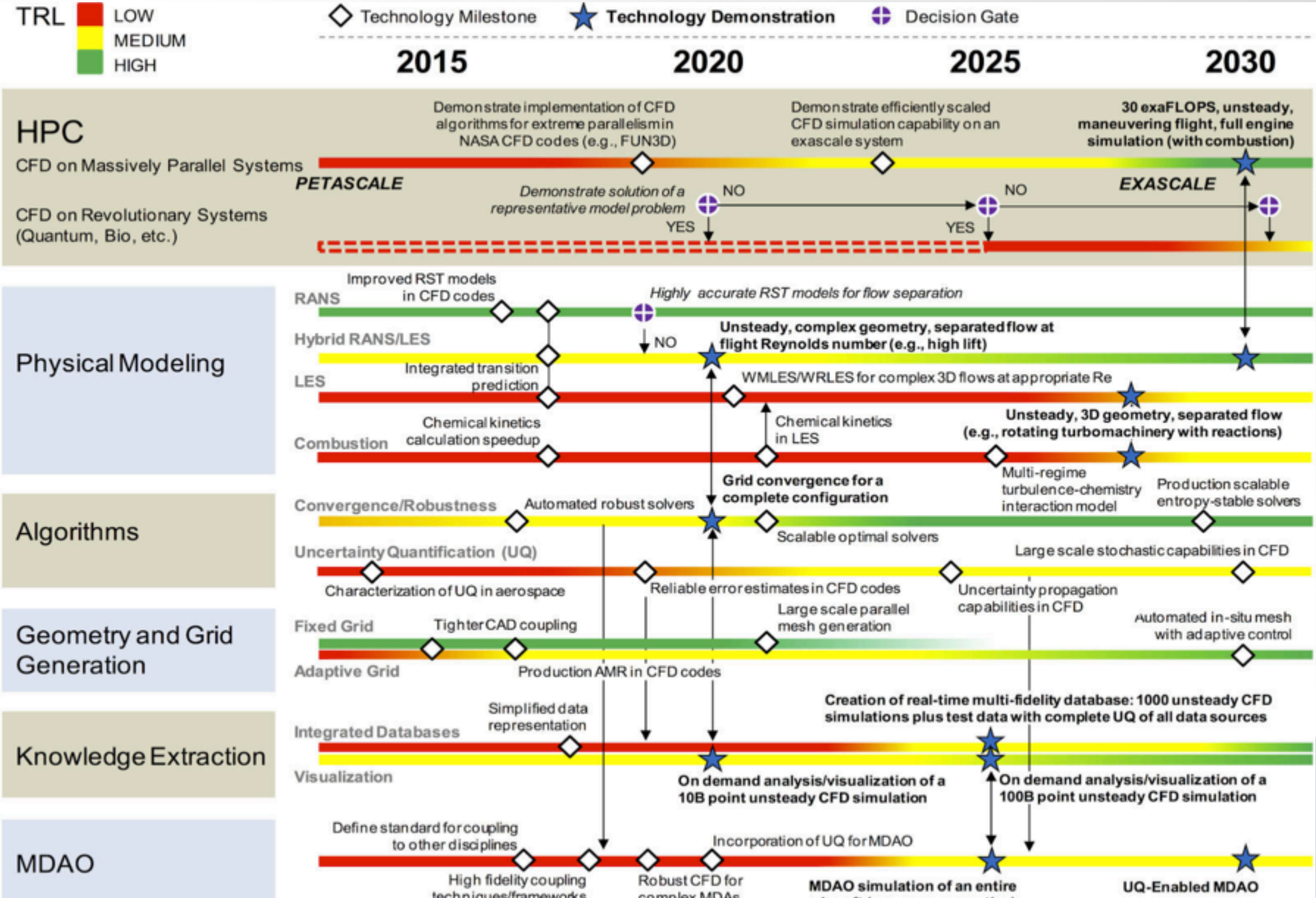
Plus the

- TILDA Vision (2014)

Can be classified as

- Realistic: NASA vision CFD-2030
- Pessimistic: P. Spalart and V. Venkatakrishnan (2016)
- Optimistic: TILDA vision

NASA Vision CFD-2030



Spalart Future CFD Vision (2012)

- We believe this estimation to be too pessimistic!
- It is based on standard second order schemes
- HOM's and HPC offer new opportunities, which can be largely exploited

Spalart, June-August 2012

BOEING

Spectrum of Approaches to Turbulence

Name	DNS	LES	DES	RANS
Empiricism	No	Low	Medium	High
Unsteady	Yes	Yes	Yes	No (can be)
# of points (Boeing wing)	10^{20}	10^{11}	10^{7} to 10^{8}	10^{7}
In Service (Boeing)	2080*	2045*	2010 (sub-regions)	1995
Vibration, Noise	Yes	Yes	Yes	No (buffet maybe)

*Assuming Moore's Law holds!

From P. Spalart and V. Venkatakrishnan (2016)

- *We believe there is a tendency towards overconfidence in CFD in some circles, even to the extent of ignoring well-known sources of error, which creates a risk of backlash, were CFD to be blamed for costly mistakes.*

- *We now summarize our predictions for turbulence treatment at the Reynolds numbers of interest*
  - ***DNS and wall-resolved LES will not be used. The challenges in physical modelling of transition and turbulence will not be truly overcome in this century (!!?)***
  - *Pure RANS cannot be fully eliminated**, but is not to be trusted after massive separation, and ultimately not even in boundary layers in strong adverse pressure gradients**.*
  - *The switch from RANS to WMLES will not happen globally, but instead, hybrid simulations will see the boundary move forward to gradually shrink the RANS region, reducing it to the thinnest areas of boundary layers, which are the least difficult to predict but cannot be ignored.*

The TILDA Vision

These estimates do not take into account the potential offered by:

- High Order Methods
- Advances in HPC and the increasing capacities of new multicore-multithread architectures
- The potential add-ons from multiple GPU's infrastructures
- Advancements in LES/DNS methodologies, through improved algorithmic developments, such as
  - Multilevel, multiscale methodologies
  - Optimal combinations of explicit and implicit methods

With a potential gain of 3 to 4 orders of magnitude!!

High Order Methods (HOM)

- Current CFD codes are nominally of second order
  - Valid strictly on Cartesian grids
  - On unstructured grids there is a general loss of accuracy due to irregular cell shape and sizes

- High order methods (HOM) on unstructured grids
  - Up to unlimited order of accuracy
  - Keeps the accuracy in each cell since the order is defined by the power of the polynomial representation in each cell
  - Provides highly accurate solutions on coarse grids
  - Various methods are available and in further development, towards higher levels of maturity:
    - Discontinuous Galerkin
    - Spectral Differences
    - Flux Reconstruction

Challenges of HOM

- Necessity for curved meshes at boundaries
- More efficient time integration methods

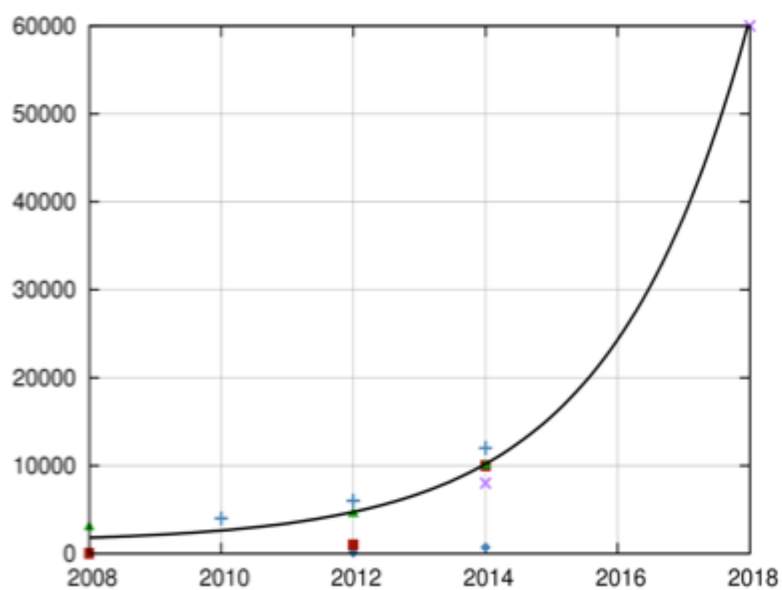
- Future potential
  - From the IDIHOM project it appears that HOM is not yet competitive compared to current efficient finite volume CFD codes, for steady RANS
  - But room is still available for performance improvements

- However, HOM's are highly competitive for unsteady flows, in particular for CAA and LES/DNS

Main objectives of the TILDA project (Coordinated by NUMECA)

Quantitative Objective:

- **Run a 1-10 Billion DoF for LES/DNS on 50,000+ cores in 1 day; that is for a cost of 1 to 1.5 MCPU-h**
- **Evolution of HPC power in Industry**



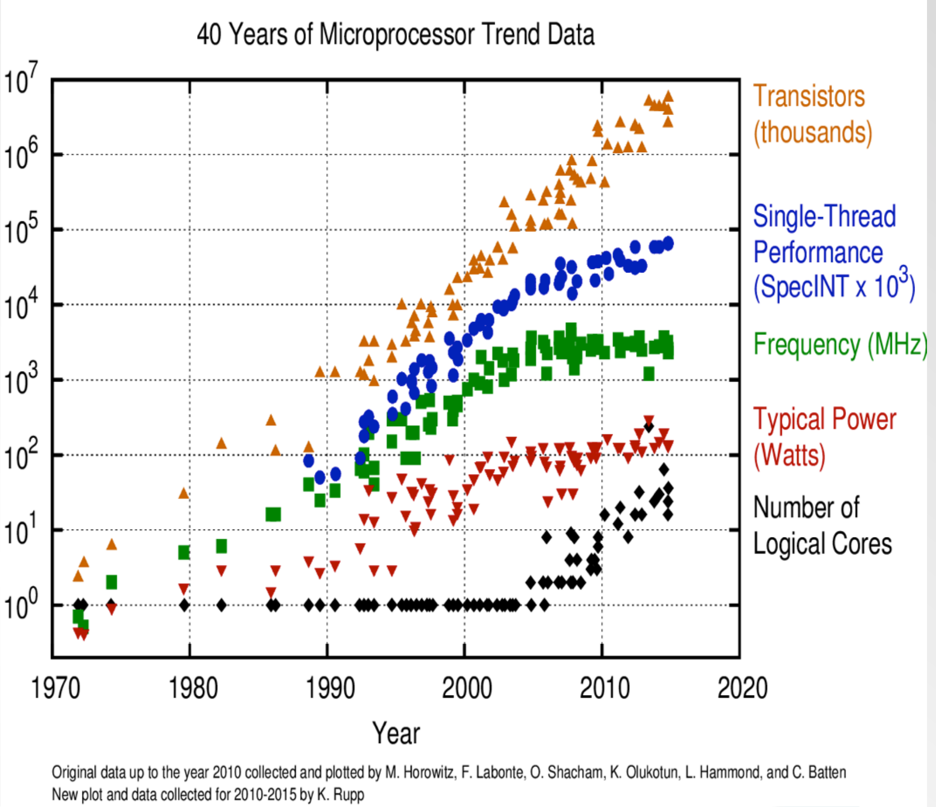
Evaluation of HPC, i.e. number of cores vs. years used/in use and extrapolated to the end of TILDA

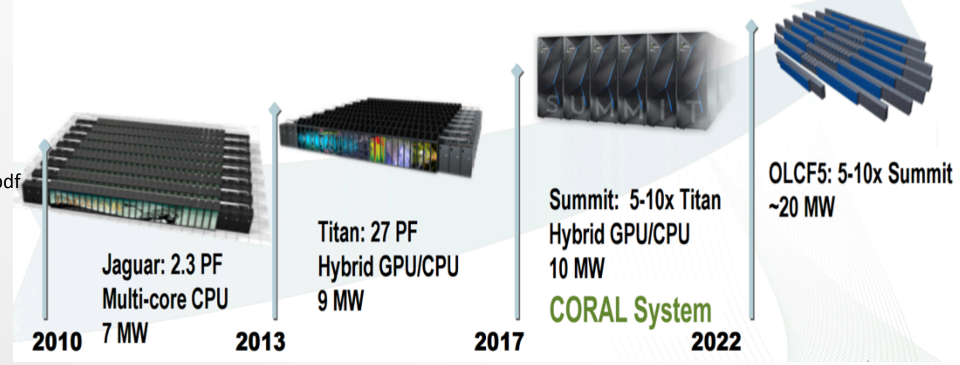
This goal can be met by introducing:

-- Efficient high-order methods (***HOM***), which offer the requested accuracy on coarser unstructured meshes and have the potential to make fully resolved simulations (***LES***, but also DNS) feasible for industry.
-- New methodologies for LES/DNS, based on multilevel, multi-resolution, adaptive and other methods
-- Exploit massive parallelism, including multi-core and multi-threaded hardware

Path to Industrial LES/DNS

- **Improvements in single thread performance has slowed, but not completely flattened**
- **Continued increases in the number of cores per processor and energy efficient accelerators mean Moore's Law will hold into the near future (~2020-2025)**
- **Harnessing the power of future systems will require software that map well onto heterogeneous, high-FLOPs, low memory bandwidth hardware**
- **High order solvers are demonstrated to efficiently utilize current leadership systems at scale[2]**
  - **Piz-Daint system: ~10 PF**
  - **PyFR: 45% of peak system utilization**
- **The current path points to exascale systems deployed by 2025, providing 100X more FLOPs for industrial LES**





[1] https://www.karlrupp.net/2015/06/40-years-of-microprocessor-trend-data/
[2] https://www.nas.nasa.gov/assets/pdf/ams/2016/AMS_20160531_Witherden-Vincent.pdf
[3] https://ideas-productivity.org/wordpress/wp-content/uploads/2015/09/06-facilities-readiness-wells.pdf

TILDA Budget and Partners

- Budget: around 3M€, for a period of three years

- NUMECA Int. (Belgium)
- DLR (Germany)
- ONERA (France)
- Dassault Aviation (France)
- SAFRAN (France)
- CERFACS (France)
- CENAERO (Belgium)
- Univ. Catholique de Louvain-UCL (Belgium)
- Univ. Bergamo (Italy)
- Imperial College (UK)
- TsAGI (Russia)

Associated Partners

- Airbus
- MTU (Germany)
- NASA Glenn – HT Huynh (USA)

TILDA Objectives

The technical objectives for bringing LES and future DNS closer to industrial applications in the mid-term, require innovative developments, ensuring future CFD approaches to offer confidence and reliability combined with accuracy and user-friendliness. Hence in the TILDA project the objectives read:

- Advance methods to accelerate ***HOM for unsteady simulations*** of LES and future DNS on ***unstructured grids***.
- Advance methods to ***accelerate LES and future DNS*** methodology by multilevel, adaptive, fractal and similar approaches on unstructured grids.
- Extend LES/DNS to industrially relevant applications using HOMs on unstructured grids for unsteady flows aiming at a reduction of ***2-3 orders of magnitude in CPU time***, together with the use of the innovative research on LES with respect to adaptivity and multilevel use with ***an additional potential gain of 1-2 orders of magnitude***.
- Provide ***grid generation methods for HOM on unstructured grids***, with emphasis on valid curvilinear meshes for complex geometries including boundary layer and hybrid meshes, while ***accounting for both mesh and solution quality***.
- Moreover, keep a focus on large scale computations with efficient mesh generation algorithms and parallel adaptation, as well as performance-oriented load-balancing and partitioning strategies.

TILDA Work Packages

WP1: General Management

- T1.1: Project Management
- T1.2: Website / Exploitation / Dissemination / Communication
- T1.3: Test-case-team management

High-Order Methods area

WP2: Acceleration of high order methods for unsteady flows

- T2.1: Implicit methods
- T2.2: Time adaptive methods
- T2.3: Robustness and efficiency of HO space-time methods

WP3: Multi-resolution methodologies for efficiency in LES/DNS

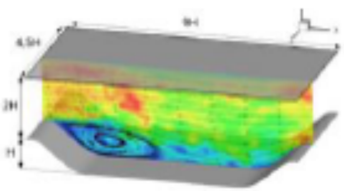
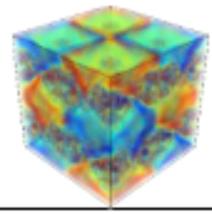
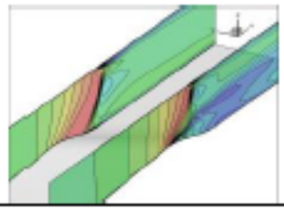
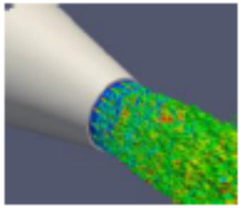
- T3.1: Multi-level approach
- T3.2: Space adaptive methods/meshing
- T3.3: Wall-modelled LES

WP4: Grid generation and HPC

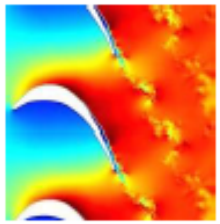
- T4.1: Grid generation for high order methods
- T4.2: Parallelisation to "several tens of thousands" cores capability
- T4.3: I/O post-processing for high-order methods

WP5: Test case repository for unsteady simulations (validation, proof-of-concept) - initiated by **baseline computations** (wall-modelled LES) **and** finalised with **advanced approaches** (LES --> DNS)

TILDA TEST CASES

Validation/verification = fundamental/basic test cases			Proof-of-concept TC
			
TC-F1: Periodic Hill Re_H=10600 LES 13x10^6 points Re_H=10600/19000/37000 (Exp.)	**TC-F2: Taylor-Green vortex** Re=1600 (DNS) Re=5000 (LES)	**TC-F3: Shock boundary layer interaction on swept bump** Ma=0.75 Re=1.13 10^6	**TC-P1: Jet with/without micro-jets – fluidic injection** Ma=0.9 Re=10^6
Justification for Test Case: RANS isn't able to deliver decent results	**Justification for Test Case:** Detailed grid convergence assessment of LES and DNS for transition on unstructured meshes	**Justification for Test Case:** Fundamental geometry but complex physics due to shock stability/position	**Justification for Test Case:** RANS can't compute turbulence effects at all
Quantifiable Objective[2]: 1 day on e.g. 50,000 cores	**Quantifiable Objective[2]:** 0.025/0.75 day on e.g. 50,000 cores – depending on Re	**Quantifiable Objective[2]:** 2-3 days on e.g. 50,000 cores	**Quantifiable Objective[2]:** 2-3 days on e.g. 50,000 cores
Area of Impact: External aerodynamics	**Area of Impact:** General aerodynamics	**Area of Impact:** Wing / turbomachinery	**Area of Impact:** Aero-acoustics

TILDA TEST CASES

Proof-of-concept = industrial demonstrator test cases, cont.				
				
TC-P2: Generic Falcon business jet in landing configuration M=0.20 α=5.0° z=0 ft	**TC-P3: T106C high-lift Cascade** Ma-in=0.28 Ma-out= 0.59 Outflow: Re= 80,000 – 150,000	**TC-P4: Noise suppressing nozzle with chevrons** Npr=2.8; Schlieren & Laser sheet; PIV: Velocity & fluctuations; Noise: 1/3 octavo meas.	**TC-P5: Boeing Rudimentary Landing Gear**[3] U=40m/s (M≈0.12) $Re=UD/\nu \approx 10^6$	**TC-P6: NASA Rotor 37** 36 multiple-circular-arc blade Tip Speed= 1500ft/sec Pressure ratio =2.106
Justification for TC: Application challenge full aircraft	**Justification for TC:** DNS and LES of natural and bypass transition in flight condition	**Justification for TC:** Environmental aspect, noise suppressing nozzle	**Justification for TC:** Landing Gear is a major noise source	**Justification for TC:** Difficult to predict near-stall performance
Quantifiable Objective[2]**:** 2-3 days on e.g. 50,000 cores	**Quantifiable Objective**[2]**:** 0.5 day on e.g. 50,000 cores	**Quantifiable Objective**[2]**:** 1 day on e.g. 50,000 cores	**Quantifiable Objective**[2]**:** 2-3 days on e.g. 50,000 cores	**Quantifiable Objective**[2]**:** 2-3 days on e.g. 50,000 cores

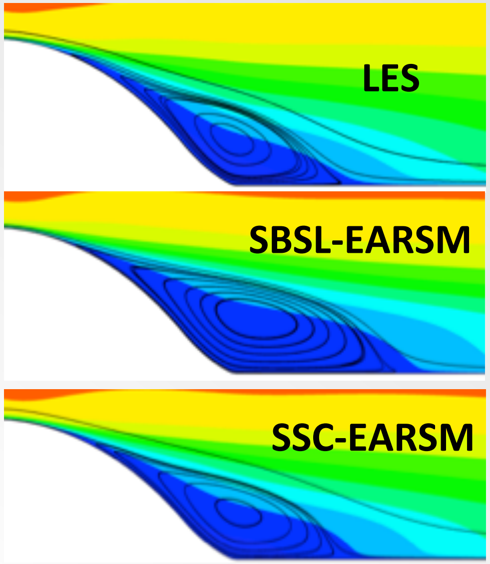
A representative example of TILDA Achievements

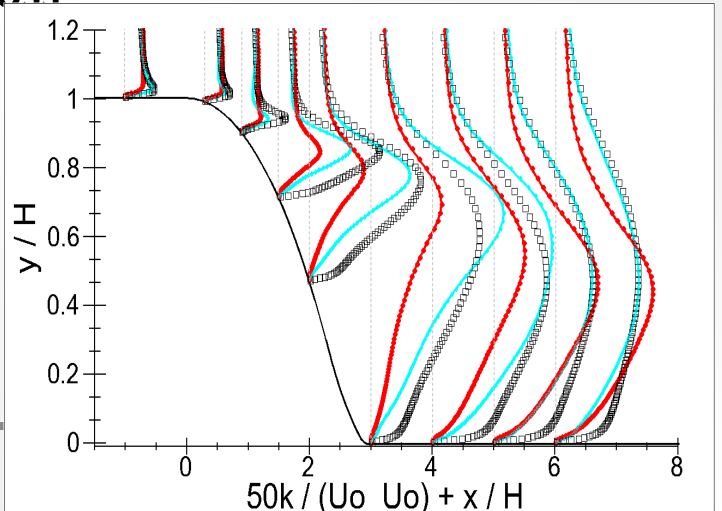
- **From P. Vincent et al, Imperial College, 2016**
- **22.5 Billion DoF,**
- **Order 4,**
- **on 5000 GPU in 35 Hours, on TITAN**

Expected outcome for industry

- Prediction of extended Flight Envelope, which have the potential to change the way industry uses CFD in the design process,
  - by ensuring highly reliable data, in support of the design decision process, with a turnaround time of 1 day
- Enhanced understanding of the underlying physics
- The generation of representative LES/DNS databases should provide a framework for improvements of Turbulence and Transition models for RANS simulations
  - These simulations provide a never seen before amount of fully detailed data to investigate all the contributions to, e.g. k; e; Reynolds stresses, ……,
  - And compare with existing models
  - And improve the models
- **This opens a large road towards more reliable RANS models, as well as more reliable subgrid scale models for WMLES**

- **Separation Sensitive Corrected Explicit Algebraic Reynolds Stress Model (SSC-EARSM)** *S. Monté, L. Temmerman, B. Léonard, B. Tartinville, C. Hirsch*, ETMM11 (2016)
- The SSC-EARSM is designed with the aim of better predicting separated flows.
- It is constructed on the SBSL-EARSM model of Menter et al. (2012), Jakirlic et al (2015) in which three corrections are introduced based on identified weaknesses of the original model.
- **Based on systematic comparisons with LES and DNS data bases, comparing data such as shear stress and kinetic turbulent energy distributions**
- **The modifications have been designed to better predict the kinetic energy production, and the shear stress, across the separation bubble**



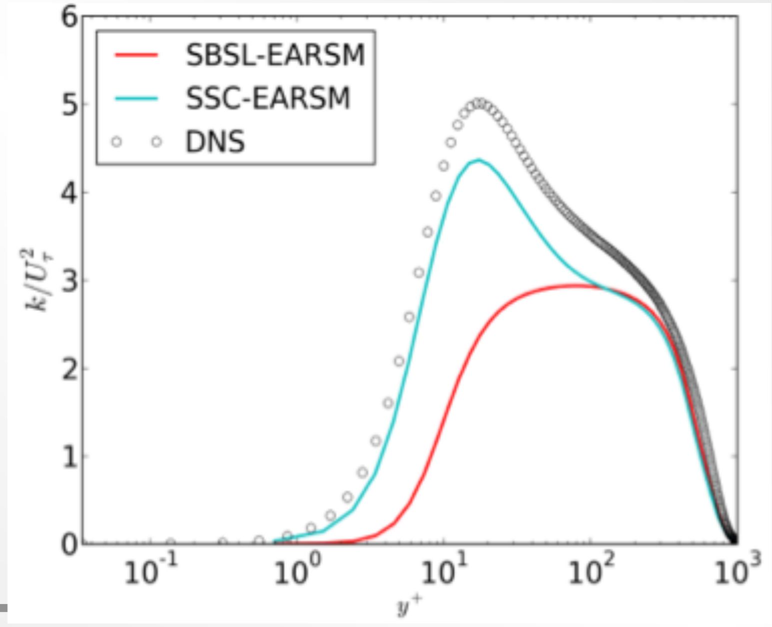


Turbulent kinetic energy in the separated bubble of the curved backward facing step.
Squares: LES of Bentaleb et al. (2011).
Red: the SBSL-EARSM model.
Blue: the SSC-EARSM model

SSC-EARSM Turbulence Model

- The development and the extensive testing of the SSC-EARSM model indicate that major weaknesses of the SBSL-EARSM model, which are common to most RANS models, can be addressed
- The development of the model was based on a large number of reference data, such as the curved backward facing step of Bentaleb et al. (2011), the periodic hill, DNS data for the flat plate, ………
- The outcome is that the SSC-EARSM model better resolves separated flows, including more complex separated flows such as the
  - Trap wing of HLPW-1
  - DrivAer car models of Heft et al. (2012)
  - CRM model of DPW-4

Turbulent kinetic energy k/Uτ^2 over a turbulent flat plate at Reϑ=2,540.
Red solid line: the SBSL-EARSM model.
Cyan solid line: the SSC-EARSM model
Dots: DNS data from P. Schlatter (KTH).

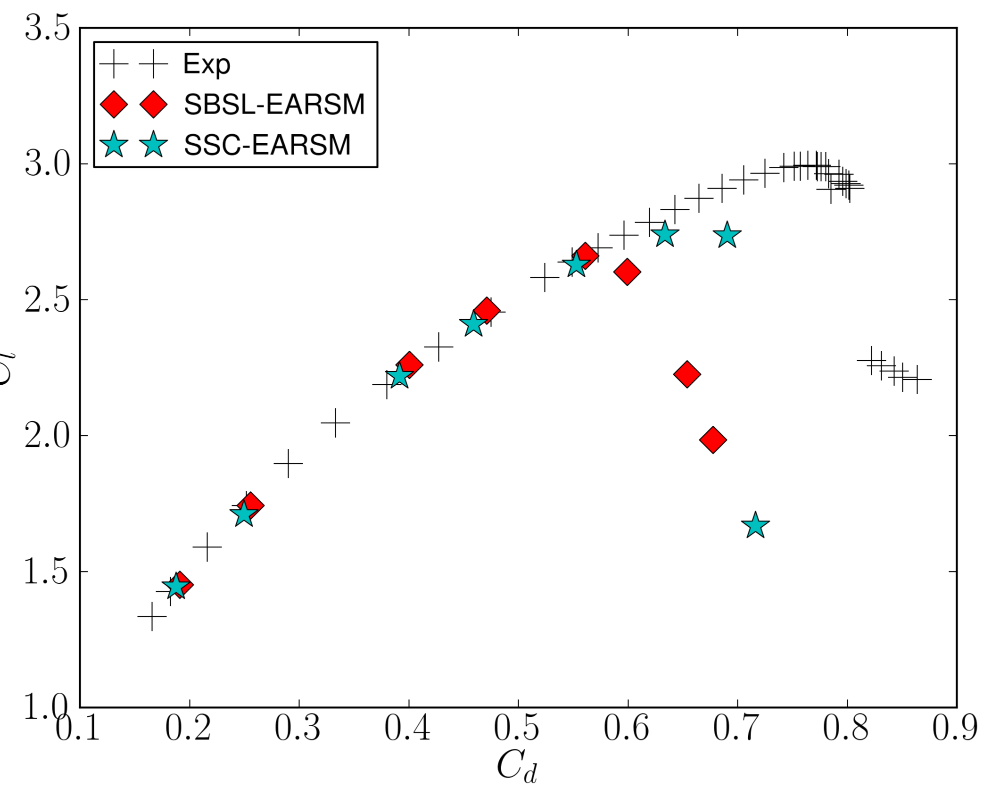


Trap Wing of HLPW-1

SBSL-EARSM

SSC-EARSM

Figure 7: Friction lines on the trap wing configuration (HLPW I) at = 28° . Top: SBSL-EARSM model. Bottom: SSC-EARSM model.

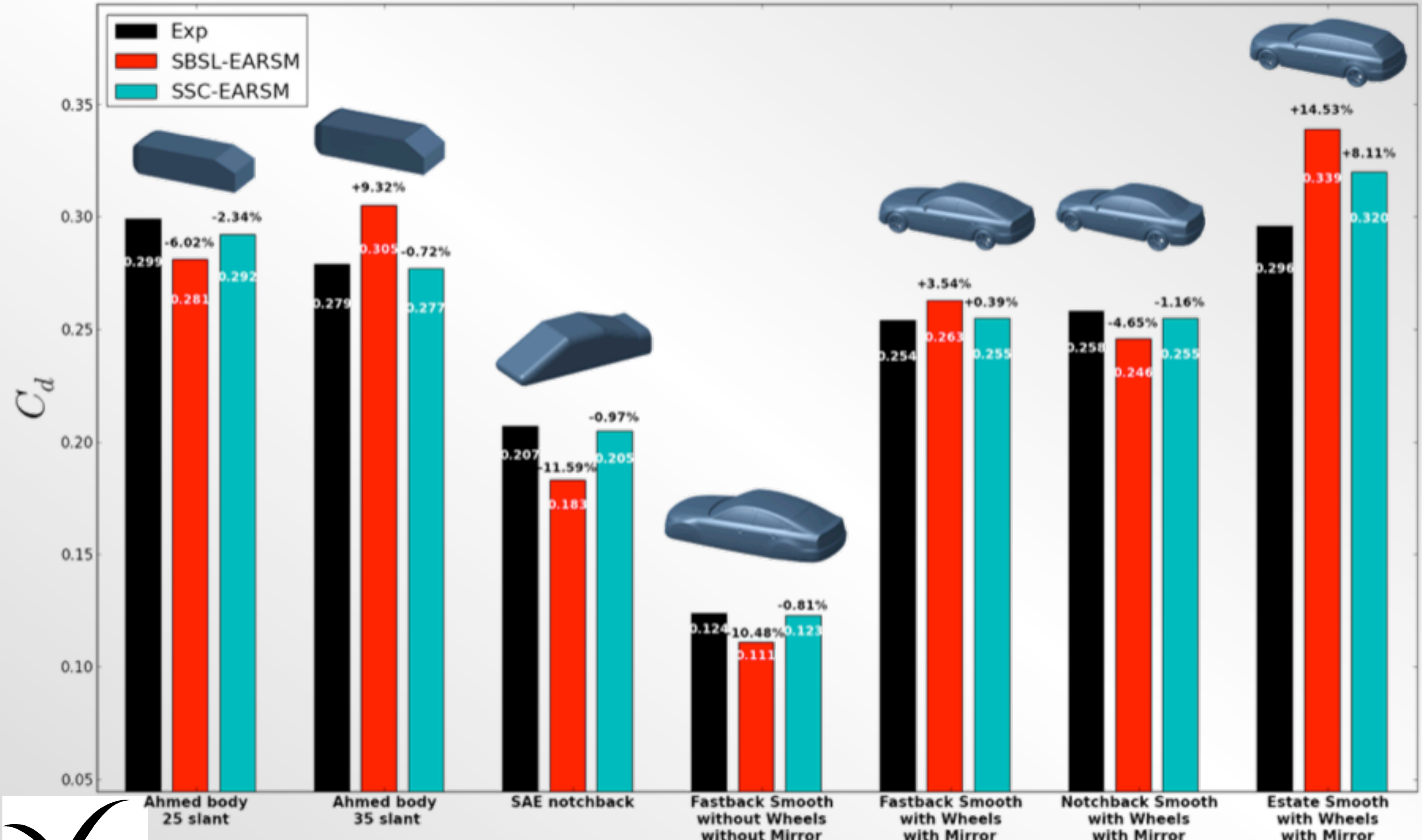


Pressure coefficient and skin friction over the DrivAer car geometries.

Exp | **SBSL-EARSM** | **SSC-EARSM**

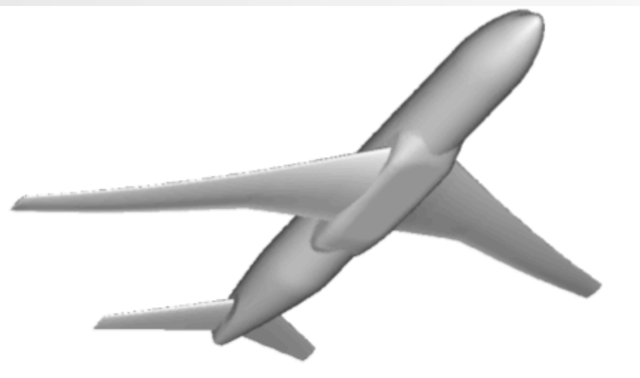
Fastback

SSC-EARSM Turbulence Model -- Drag prediction



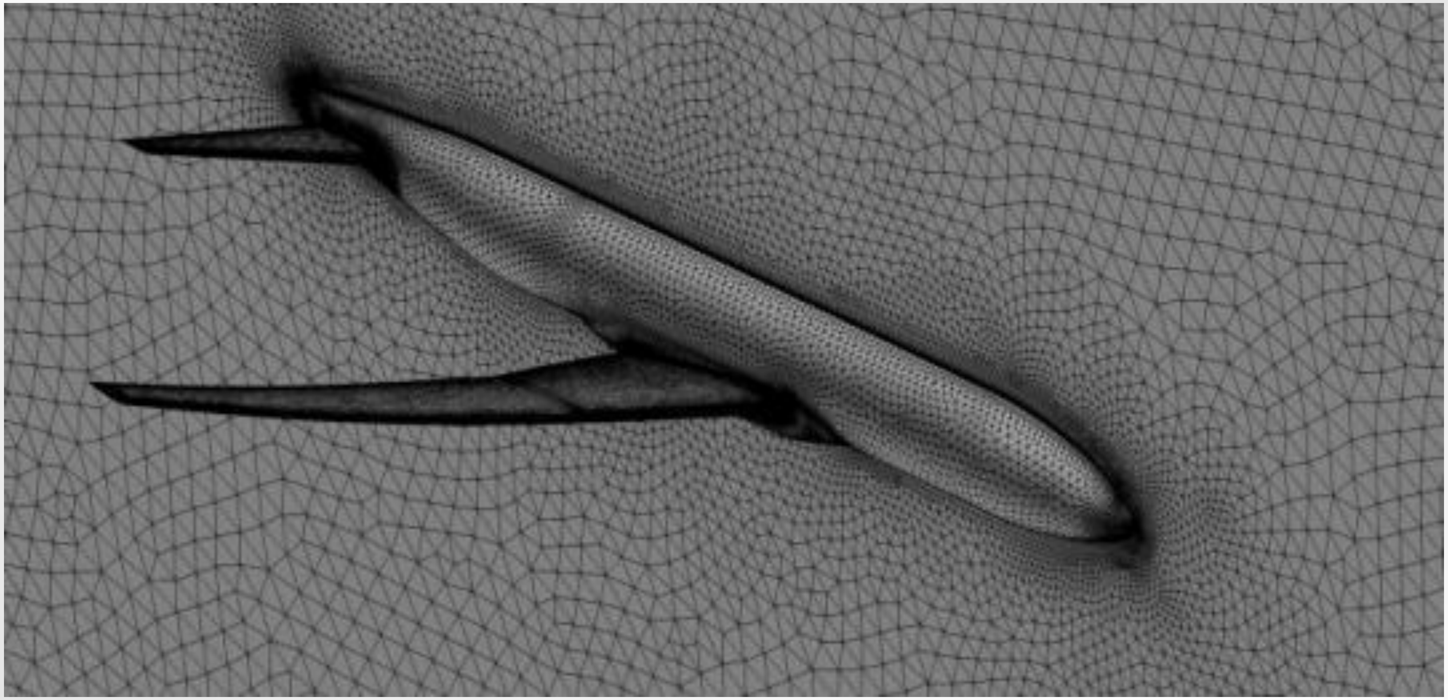
AIAA DPW4

- NASA Common Research Model in its Wing-Body-Tail configuration
- Representative of contemporary transonic transport aircraft
- Wing profile designed for the purposes of research and development:
  - Strong adverse pressure gradient over the last 10%-15% of local chord
  - Promote separation of boundary layer to amplify effect of turbulence model
- Experimental data from NASA Ames 11ft transonic wind tunnel and from JAXA, taking into account elastic deformation

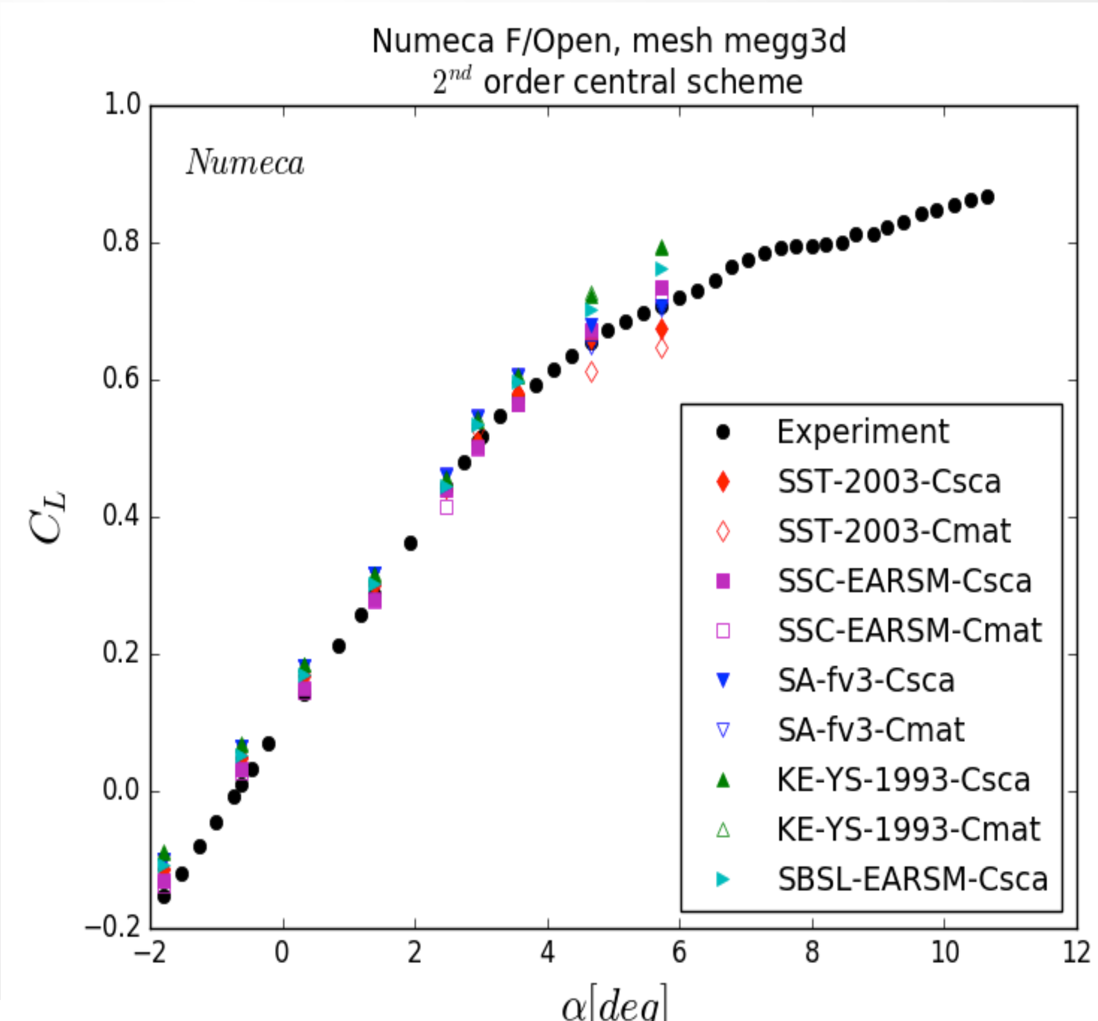


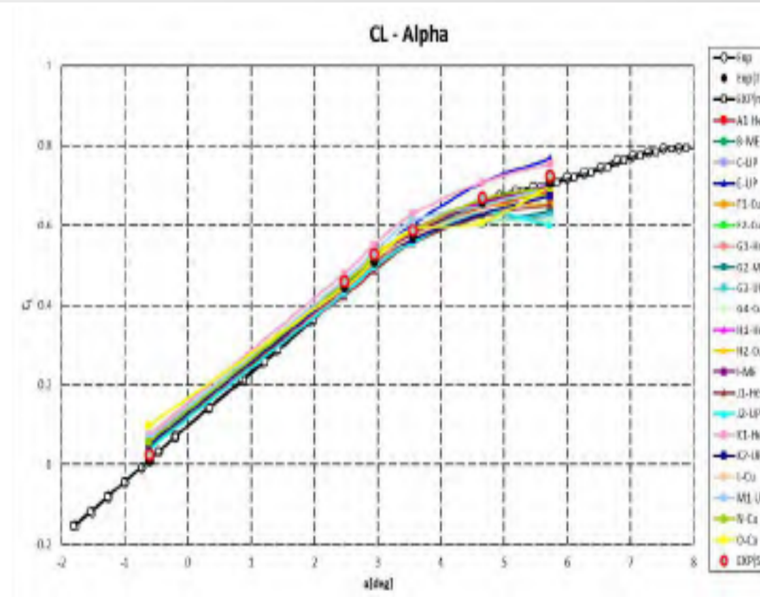
JAXA grids and experimental data

- Unstructured grid from JAXA
- Solver: FINE™/Open from NUMECA with SSC-EARSM model



JAXA grids and experimental data: CL-Alpha

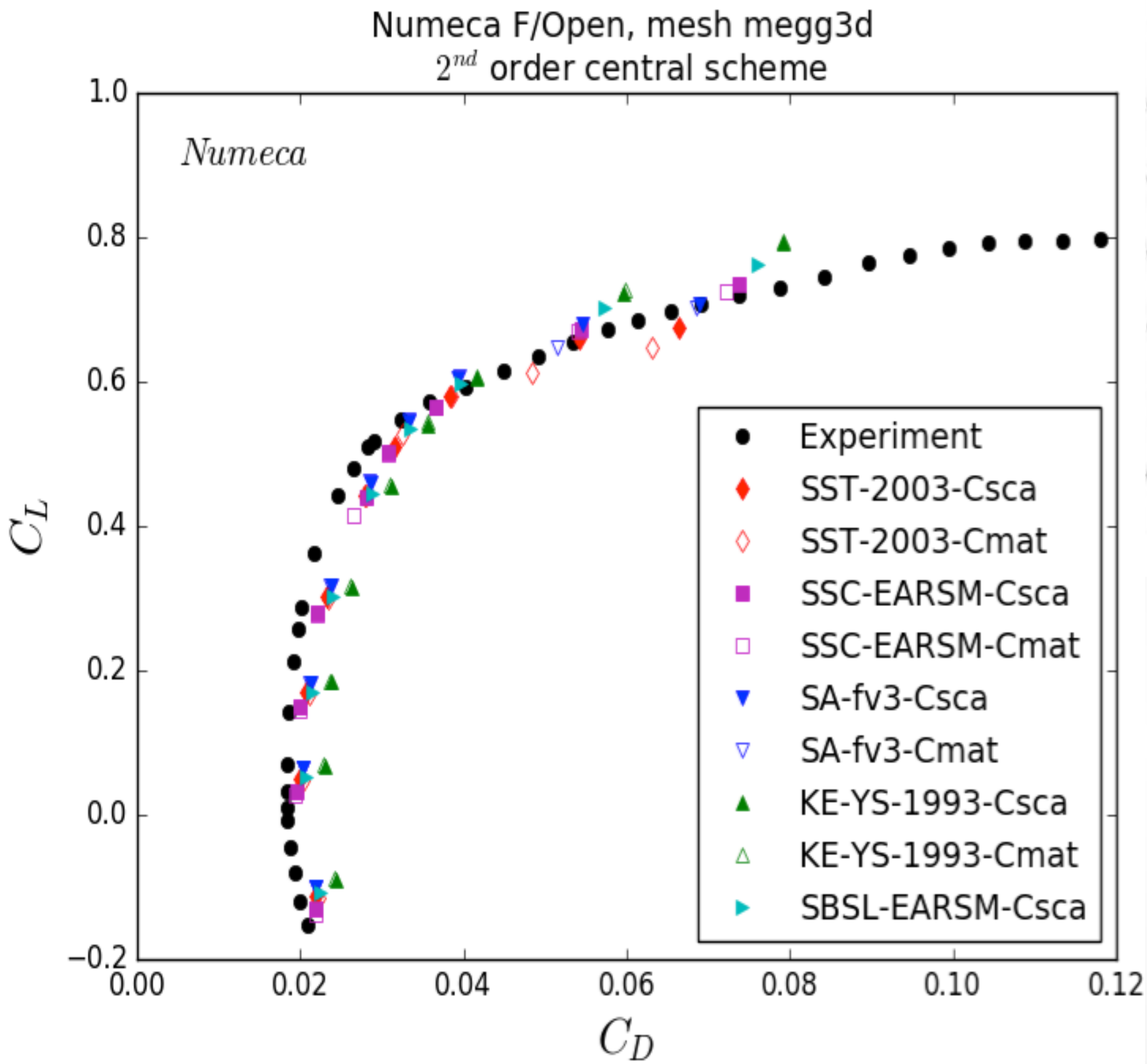


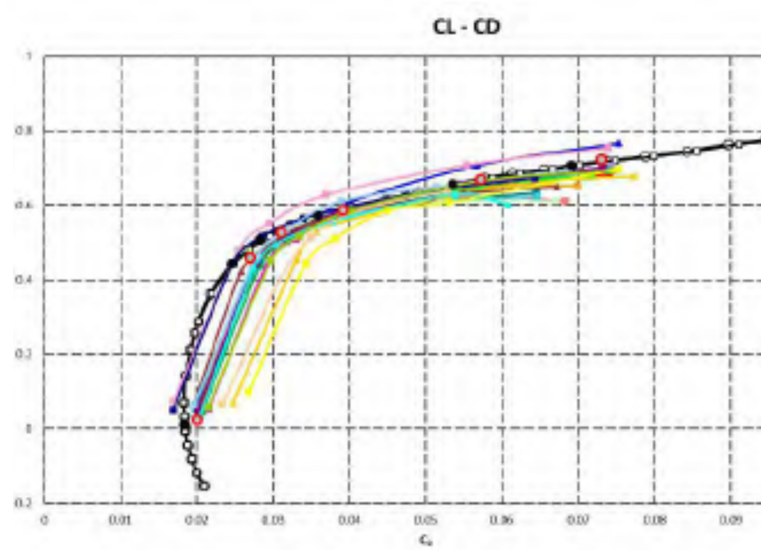


(a) Lift curve

Data from JAXA
APC-1 Workshop

JAXA grids and experimental data: Polar

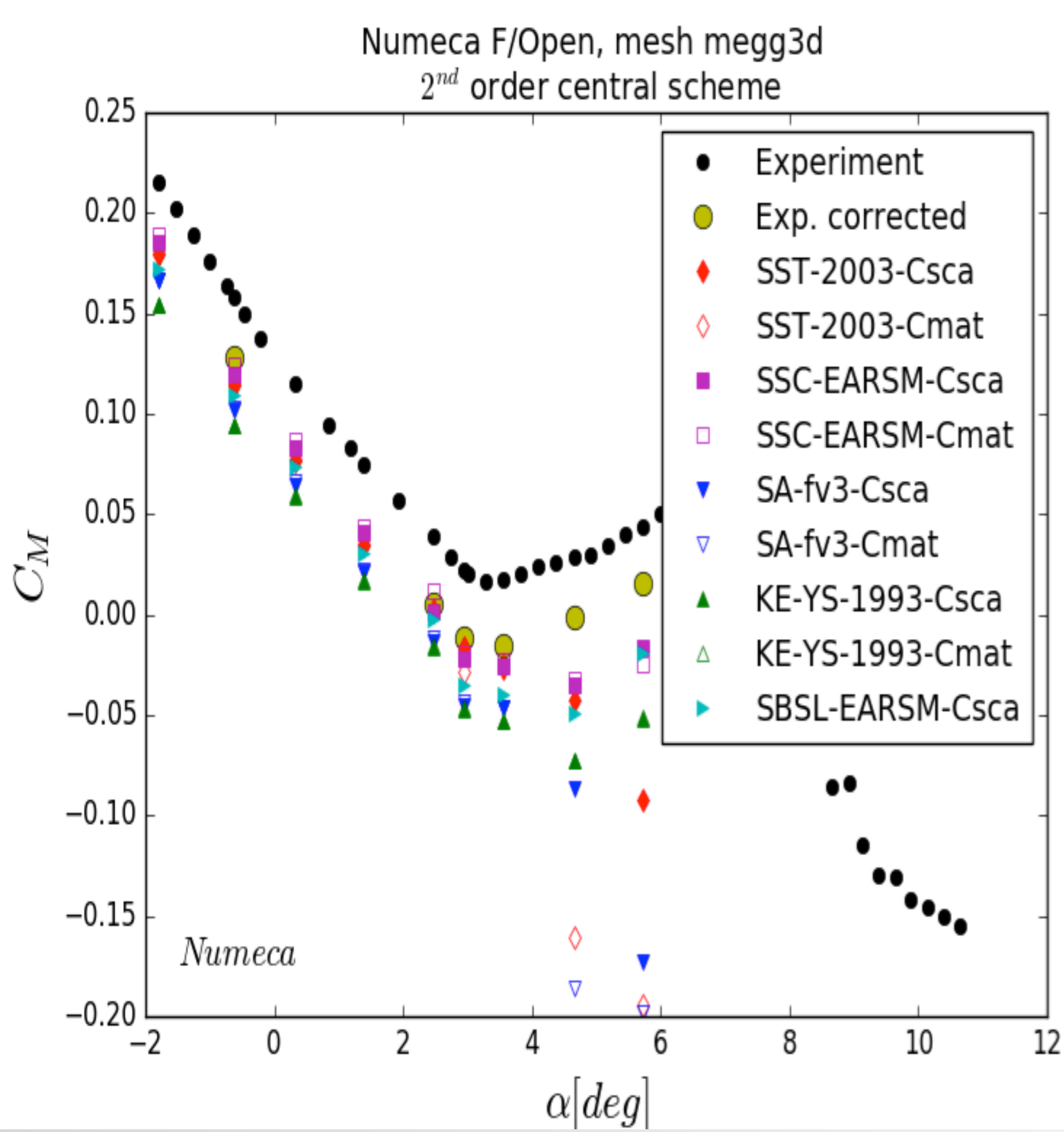


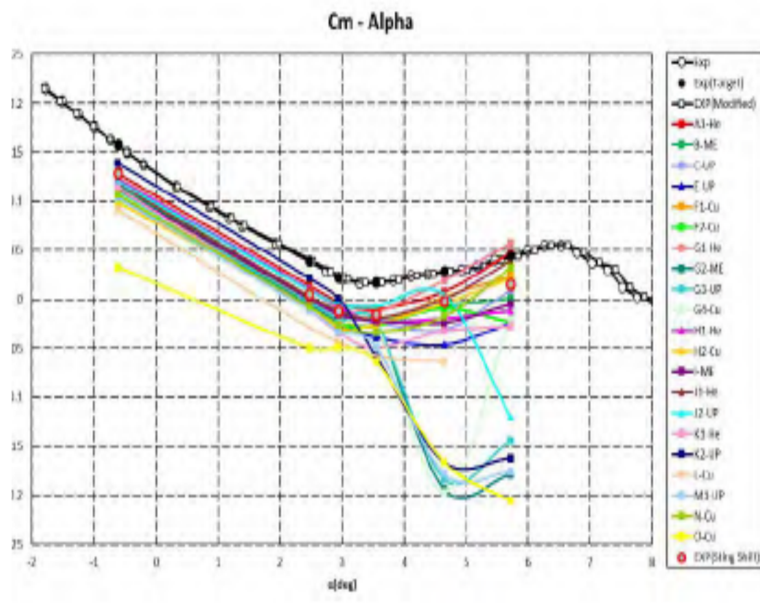


(b) Drag polar

Data from JAXA
APC-1 Workshop

JAXA grids and experimental data: CM-Alpha





(c) Pitching moment curve

Data from JAXA
APC-1 Workshop

Next

- The TILDA projects is active until November 2018
- A "**TILDA" Symposium is planned, by November 2018:**

High Fidelity LES/DNS for Industrial Applications

- Expected to initiate a new dedicated bi-annual series of conferences, covering a.o.
  - **Improvements in HOM and grid generation for LES/DNS**
  - **Industrial relevant applications**
  - **Understanding of the fundamentals of turbulence and transition**
  - **Exploitation towards improvement of WMLES, RANS and transition modeling**
- Will be organized by the newly formed "Aerospace Europe" community, composed by the major EU scientific and industrial Aeronautical Associations:
  - CEAS, ECCOMAS, EUROMECH, ERCOFTAC, EUROTURBO, EUCASS
  - An Association with AIAA is under consideration

Conclusions

- Various presentations to follow will present some of the current progress within the TILDA project

- Many issues about the small scale near-wall treatment are to be investigated

- It is expected to allow, in the near future, extensive HOM simulations for fully resolved LES/DNS with high resolution at increasing Re-numbers.

Thank you for your attention